Gamma-ray emission from pair cascades at the border of broad line regions

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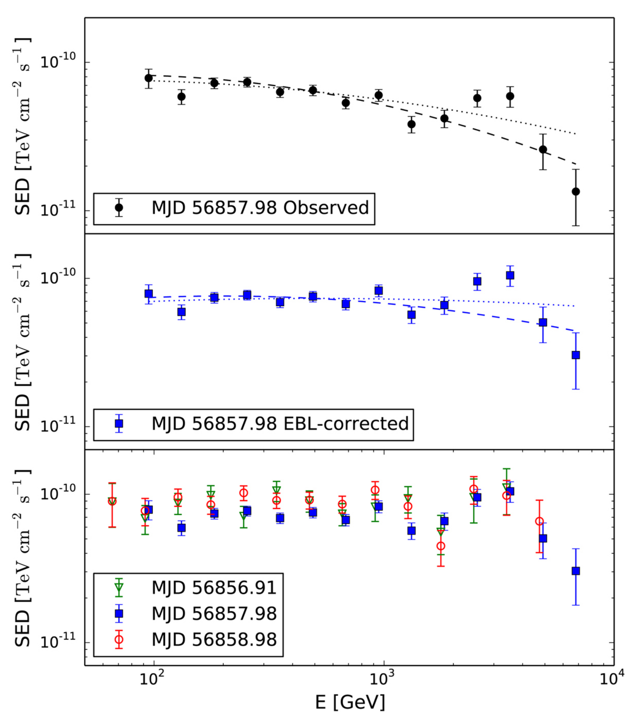
Peculiar feature in Markarian 501 – A hint to gap activity?



During a multi-wavelength campaign in 2014, the MAGIC telescopes have seen hints of a peculiar feature at 3 TeV in the SED of Mrk 501. The narrow bump seems like an additional component on top of the SSC background.

Power law, logparabola (LP) and eplogparabola fits of MAGIC data are inconsistent at $> 3\,\sigma$. A likelihood ratio test prefers a broad LP + a narrow LP at $4\,\sigma$ versus a single LP.

SED of Mrk 501 from 19.07.2014 (top and middle frame) and from 18.-20. 07. 2014 (bottom), observed by the MAGIC telescopes.
Dotted lines: Best log-parabola fit Dashed lines: Neglecting data above 1.5 TeV Acciari, et al., 2020, A&A

Model: Interaction of electron beam with emission line photons

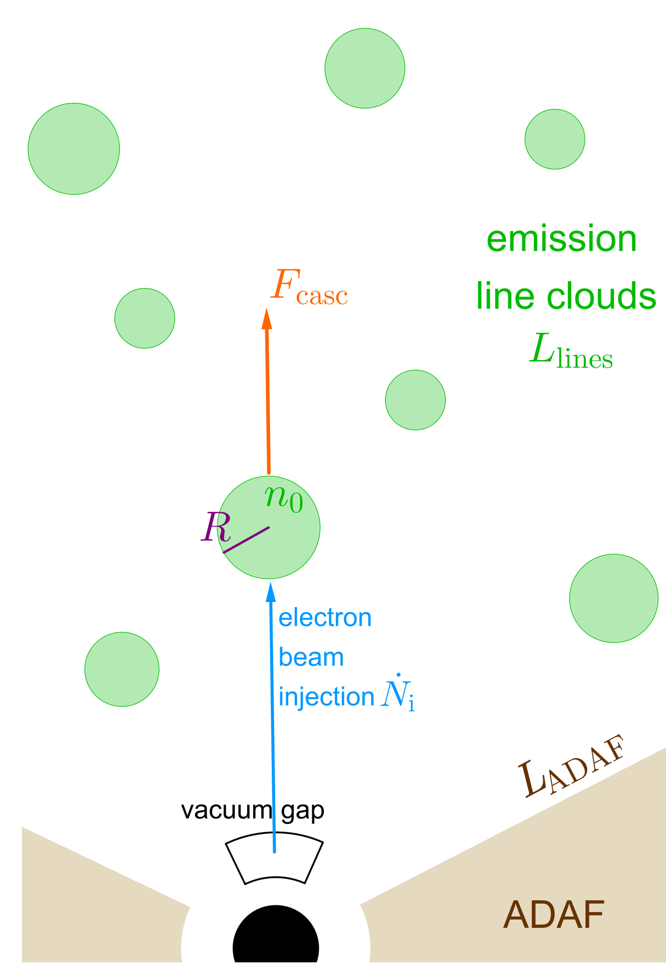
The narrow bump can be a signature of vacuum gap activity. A vacuum gap is a charge-depleted region in the magnetosphere exhibiting a huge electric field parallel to the magnetic field. So, electrons are accelerated to ultra-relativistic energies. The electron beam encounters a region with emission line photons from ionised clouds. The electrons interact with the soft line photons. By the interplay of injection, escape, pair production and IC scattering, a cascade evolves.

$$\dot{N}_\mathrm{i}(\gamma) = \frac{K_\mathrm{G}}{\sigma\sqrt{(2\pi)}} \cdot \exp\left(-\frac{(\gamma-\gamma_\mathrm{mean})^2}{2\,\sigma^2}\right)$$

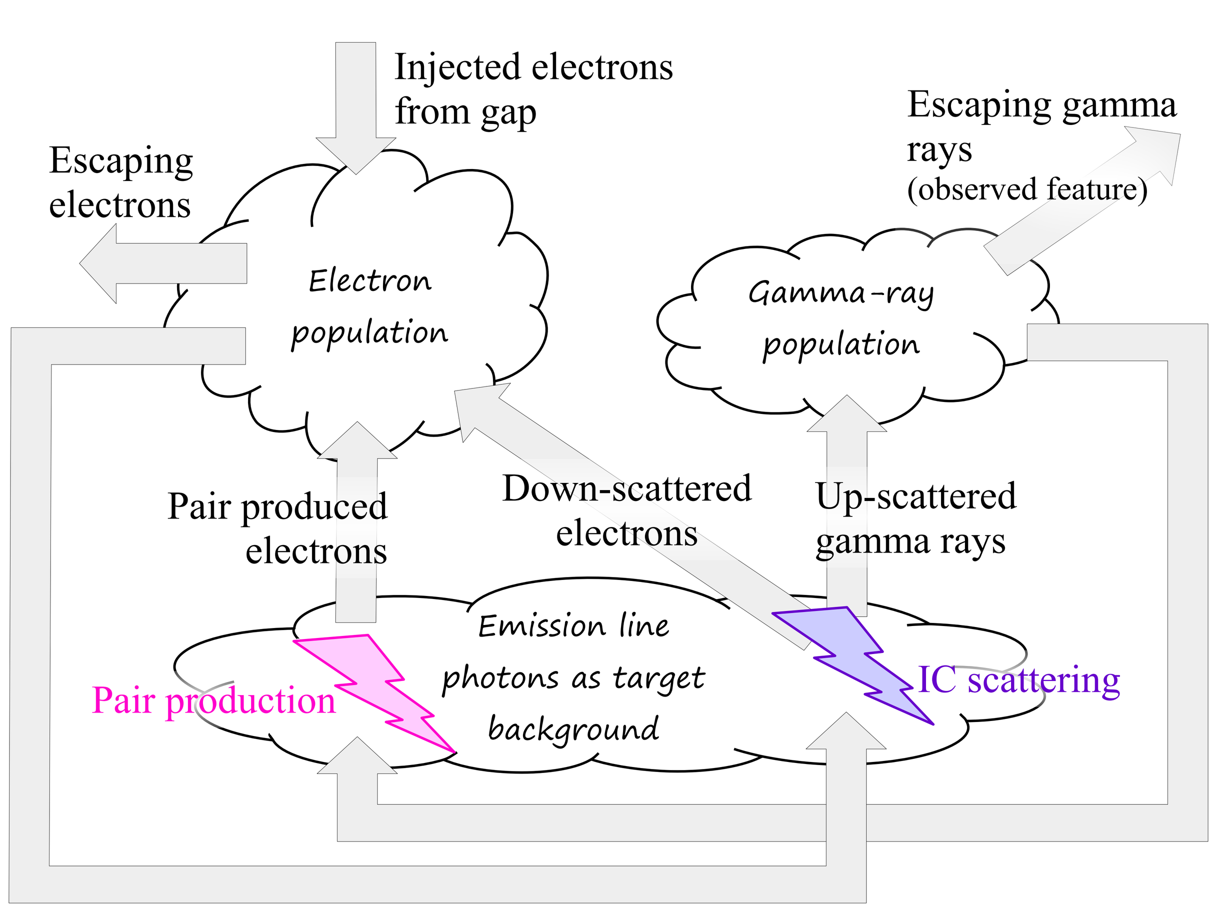
$$n_0(x) = K_\mathrm{lines} \cdot \sum_{i=1}^{4} \frac{K_{\mathrm{line},\,i}}{x_{0,\,i}} \cdot \delta_\mathrm{Dirac}\,(x - x_{0,\,i})$$

i	Wavelength $\lambda_{0,\,i}/\mathrm{nm}$	Relative flux density contribution $K_{\mathrm{line},\,i}$	Line
1	30.5	2.00	He II Lyman-α
2	93.0	0.17	H Lyman series
3	102.6	0.57	H Lyman-β
4	121.5	5.40	H Lyman-α

Escape timescale $T_\mathrm{esc} := \frac{R}{c}$



Interaction of electron beam with emission line photons ⇒ Evolution of IC pair cascade

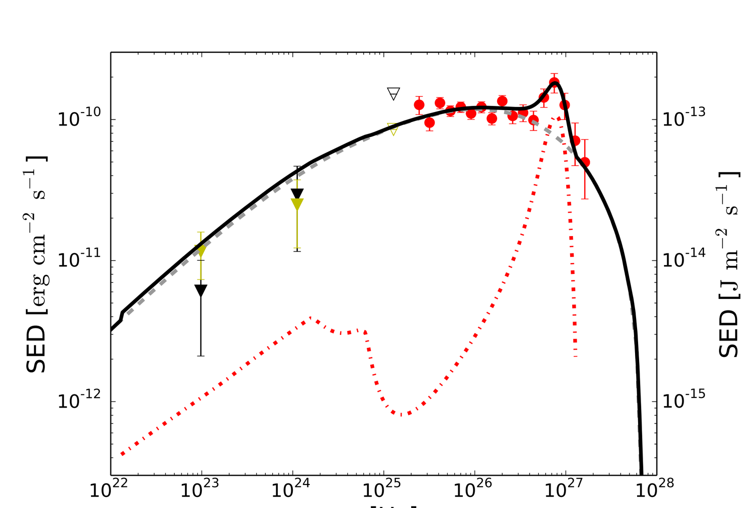


Fit to observational SED

- Assume input parameters
  ⇒ Compute electron distribution
  ⇒ Determine γ-ray photon distrib.
  ⇒ Obtain cascaded flux F_casc
- Add SSC component:
  $F = F_\mathrm{casc} + F_\mathrm{SSC}$
- Fit peaky feature:

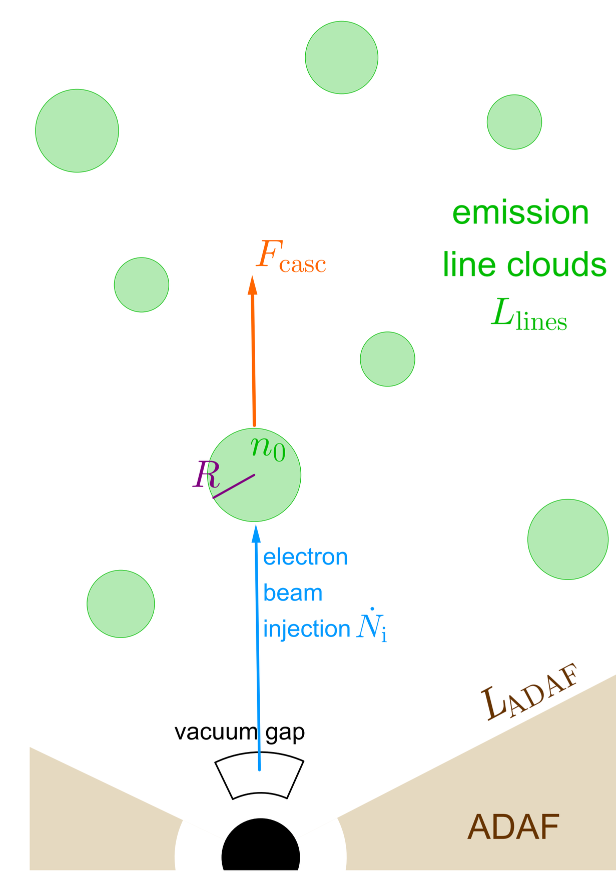
Quantity	Used value
ϕ	$1.8°$
R	$3.0 \cdot 10^{11}$ m
K_G	$3.3 \cdot 10^{4}\ \mathrm{s^{-1}m^{-3}}$
K_lines	$9.7 \cdot 10^{12}\ \mathrm{m^{-3}}$
γ_mean	$3.4 \cdot 10^{12}\ \mathrm{eV}/(m_\mathrm{e}c^2)$
σ	$0.23\,\gamma_\mathrm{mean}$

The cascade parameters used for fitting.



HE and VHE SED of Mrk 501 from 19.07.2014 (MJD 56857.98).
Red dots: MAGIC
Black / yellow triangles: Fermi LAT
Grey lines: SSC emission
Red line: Cascaded emission
Black line: SSC + cascaded emission
Wendel, et al., 2021, A&A

Inferences about Mrk 501



- Mrk 501 is found to have an advection-dominated accretion flow with electron temperature $T_\mathrm{e} \approx 10^{10}$ K and accretion rate $\dot{m} \approx$ few 10^{-4}.
  - Pair production in gap and subsequent multiplication by the factor 10^6 produce an ultra-relativistic electron beam.
  - Emission line clouds reprocess a fraction ≈ 0.01 of the accretion flow luminosity into BLR luminosity.
- The electron beam + the broad emission line photons initiate an IC pair cascade.
- The escaping gamma rays can account for the narrow 3 TeV SED feature.
- The narrow SED feature can indicate gap activity.

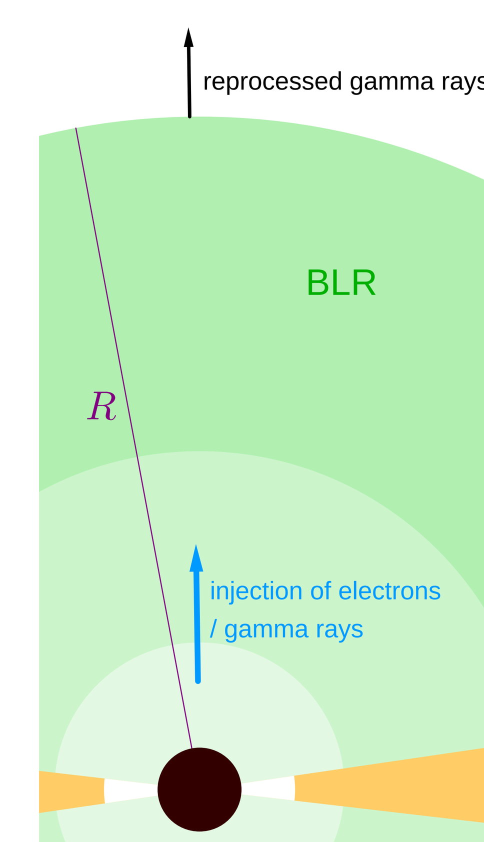
Gamma-ray emission from 3C 279 - The model

The Fermi LAT SED from January 2018 is difficult to describe by conventional SED fitting. Similarly to the Mrk case, a cascade in the strong BLR photon field is applied:

Injection: Ultra-relativistic electrons and/or HE gamma rays with hard spectral shape

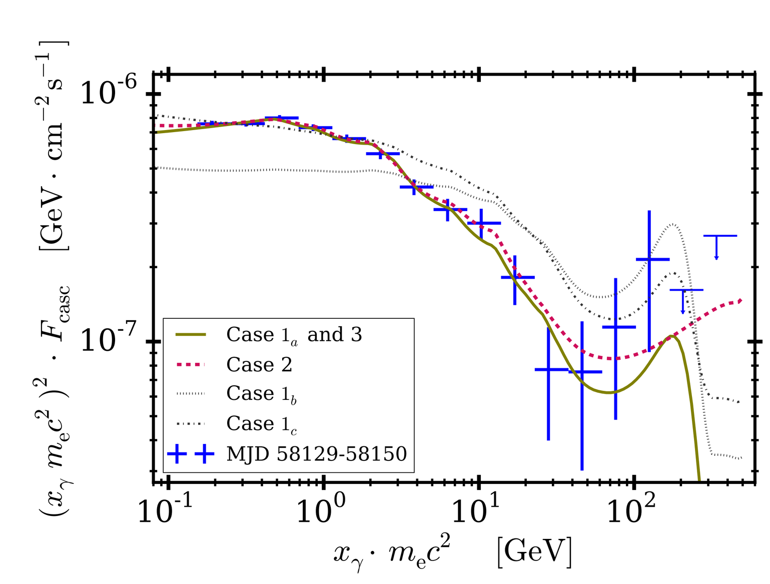
$n_0(x)$: Sum of BLR emission lines
Most prominent lines: O VII, C V, Fe XVIII, Fe XXIII, He II Lyman-α, He I, H I Lyman-α

Escape timescale $T_\mathrm{esc} := \frac{R}{c}$



Not only pure pair absorption is considered, but also reprocessing in IC pair cascade is taken into account. Similarly to the Mrk case, the cascade is computed and the escaping gamma-ray flux is determined.

Gamma-ray emission from 3C 279 - The results



SED of 3C 279, observed by the Fermi LAT between MJD 58129 and MJD 58150 (January 2018, blue markers) with cascade modelling fits.
Brown and red lines: Cascade in BLR photon field
Grey lines: Cascade outside of BLR
Wendel, Shukla and Mannheim, 2021, ApJ

The model is fit to the observational SED, as seen in the brown and red lines. Furthermore, injection and cascading outside of the BLR is modelled by using the same escape radius R, but a diluted soft photon density n_0. This causes less pair absorption and a stronger influence of escape. With these prerequisites, it is found impossible to achieve a good fit, concluding that the dip in the Fermi SED might be a signature of reprocessed emission in or at the edge of the BLR.

⇒ Precision γ-ray observations reveal complexity beyond the predictions of spherical blob models but in line with the predictions of pair cascade models in external radiation fields.

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